

Physicochemical and microbiological dynamics in composting of organic waste using a new bioreactor model

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Abstract

Background

It is important to use renewable resources to minimize the environmental risks and the composting is one of the most sustainable methods for the management of organic waste.

Methods

The objective of this work was to evaluate the physicochemical dynamics of microorganisms and to study cultivable microorganisms during the composting process of organic residues in a new model of bioreactor. The formulation of a possible cocktail of microorganisms selected for use as a compound accelerator will be further investigated. In addition, the use of two inoculants (non-commercial inoculum (NCI)) and commercial inoculum (CI)) and a control without inoculant during the composting process will be analyzed to evaluate its efficiency. Composting was performed by mixing organic waste from the garden waste and University Restaurant, obtaining an ideal C/N ratio of 30:1. The composting process was carried out in 1 m³ composters with controlled temperature and aeration.

Results

The thermophilic phase for all treatments was reached by the second day. Mature compost was obtained after an average of 120 days and composting in all treatments showed an increase in the availability of P and micronutrients. During composting, the population of bacteria and actinobacteria were higher than those of yeasts and filamentous fungi.

Conclusions

Increased composting efficiency was observed when starter cultures were used, the treatments presented advantages such as greater mineralization of P-available and micronutrients as Mn and Zn, in terms of the quality of the final product in comparison to the control treatment.

Background

Food scraps and organic wastes are considered as the largest components of urban solid waste and account for approximately 55% of total waste in developing countries, which face greater challenges with food waste management [1, 2]. The treatment of organic waste is a serious and urgent matter, and since such waste negatively affects environmental quality, sustainable technologies must be implemented to reduce the environmental threat of organic waste [3].

Organic waste treatment methods commonly used in developing countries include use as feed (rare), compost (1 to 6%), anaerobic digestion (< 0.6%), incineration and/or landfills (> 90%) [1]. There have been several studies on composted materials, such as biogas slurry and cow manure [4], digested sludge mixed with mature compost and sawdust [5], green waste with spent mushroom compost and biochar [6], cattle manure and rice straw [7], and flower waste [8].

Compost produced for agricultural use from food waste has received considerable interest [9][9]. Beyond that, the composting can contribute toward huge CO₂ and energy consumption reduction [10].

Composting involves the transformation of organic matter through the rapid succession of microbial populations into a stabilized product and is considered as an efficient and inexpensive technology for the recycling of organic waste [11].

During the composting process, specific parameters are important to monitor the process and ensure that a final quality product is obtained, such as the C/N ratio, oxygen availability, pH, temperature, aeration, humidity, particle size, fermentation and presence of humic acid that is usually produced at the end of the composting process [12–14]. Traditional composting involves problems such as inadequate ventilation, uneven mixing, and other challenges, and these disadvantages can be reduced by using reactors that help control the process and provide optimal conditions for quality compost [15, 16]. In addition, pile turning during the degradation stage is key parameter to maintain microbial diversity and, to some extent, the population profile present at the beginning of the process [17].

The physicochemical characterization of organic and food residues used in composting processes, could help to determine the level of biodegradation of these residues and these data can be useful to demonstrate the possible maturation phase of composting, which provides a better and more accurate agricultural application [18].

The composting occurs with natural microbiota including bacteria, actinobacteria, yeasts and filamentous fungi, which are generally involved in the degradation of lignocellulosic components during aerobic composting [19][19]. The addition of starter cultures at the beginning of the process can lead to substantial improvement in the waste degradation rate [20–23].

During the composting process, there is a change in temperature due to the biological activity of microorganisms classified as mesophilic (15–45 °C), thermophilic (45–80 °C) and hyperthermophilic (> 80 °C) [24]. During the thermophilic and hyperthermophilic phase, normally actinobacteria and gram-positive bacteria are observed [25], occurring the suppression of several pathogens [26]. After this phase, occur the stabilization of compost temperature and the mineralization of organic compounds [27].

The composting process depends on the combinations of composting mass and its relevant ratios, i.e., the carbon: nitrogen (C:N) ratio and the presence or absence of inoculants. Suitable ratios for the combination of waste and inoculants are required to produce high-quality mature compost. The metabolic analysis of the composting process can help better understand the process parameters. The utilization of biological methods such as the inoculation of selected microbial strains can provide high

efficiency for waste management, as these microorganisms help speed up the particle decomposition process and reduce the composting process time [28].

Aim Of Paper

Due to controversial data on the efficiency of microbial inoculation and the need to improve the approach to the composting process, the aim of this study was to evaluate the efficiency of the new model of bioreactor with forced aeration system about the time of the material to be composted, the physicochemical dynamics of microorganisms and to study the cultivable microorganisms during the process of food waste composting for to later select starter cultures for the formulation of a possible cocktail of selected microorganisms to be used as compost accelerator, comparing the effectiveness of two inoculants (non-commercial ((NCI)) and commercial ((CI))) in relation to the control treatment over time in the composting process.

Methods

Step 1. Inoculum preparation

The experiment was carried out using two different inoculants, one noncommercial (NCI) and one commercial (CI - biological product made up of a mix of microorganisms, being basically lactic acid bacteria, with species not defined by the manufacturer, used for accelerating composting of organic solid waste from agricultural and household waste. According to the manufacturer, it promotes exponential increase in microbial activity, improving the fermentation and composting process by converting organic matter into nutrients such as acids and nitrogen compounds quickly and safely).

The noncommercial inoculum was prepared using 700 g of unsalted rice cooked - not to change the composition of rice, in distilled water (Fig. 1). After cooking, the rice was placed in a plastic tray covered with canvas, which was placed in the native forest on the Federal University of Lavras, during the spring, with mild temperatures. Soil litter was placed over the tray to collect the natural microbiota of the environment. The collection period was of 15 days.

Afterwards, rice with microbial growth was deposited into a 20 liters container, homogenized with 1 liter of sterile sugar cane juice, and then made to a total volume of 20 liters with distilled water. For 20 days the container was stored in a cool, ventilated and closed space [29].

The commercial inoculum was prepared according to the manufacturer's instructions in which the recommended amount of distilled water and sugar was added to the concentrated product, and after fermentation for 20 days at room temperature, the product was ready for use. Compost without the addition of inoculants was used as the control treatment.

Step 2. Preparation Of Compost Mixture

Compost mixture was performed by mixing organic waste from the Lavras University Restaurant (RU) and garden waste. For the calculation of the proportion of organic residues and residues from the landscaping that were added to the composters, so that if the ideal C/N ratio was reached for the start of composting, the initial characterization of the waste components was performed, described in the Table 1.

Table 1
Initial characterization of residues.

Material	Carbon	Nitrogen	Relation C/N
Garden waste	39	0,6	65/1
Organic waste (RU)	35,16	2,93	12/1
*RU = University restaurant			

The present work used a new type of bioreactor built with concrete blocks and an air injection system. The composters had 1 m³ (1 m x 1 m x 1 m), with monitored temperature and aeration to ensure a minimum oxygen concentration of 10% [30]. Temperature sensors were placed inside each compost (PT10 digital thermometer model MPT2, Lexitron-Guemisa, Madrid, Spain). Forced air (6.3 m³ / min) was supplied from the bottom of the pile through 5 cm diameter PVC tubing at the base of the composting cell, traversing the cell horizontally 10 cm from the rear edge, with 1 cm holes in diameter, in 3 points of the tube (25 cm, 50 cm and 75 cm), connected to a Ventibras air injection pump, with 5 horse axial fan, for 30 minutes every 3 days (Supplementary material, Fig. S1).

The mixture was characterized physicochemical before the addition of the inoculum and the beginning of the fermentation process with a C:N ratio (30:1) and a moisture content of approximately 50 to 60% of the field capacity. The height of the compost piles was monitored during sampling with a tape measure to monitor the compaction of the material and the decomposition of the particles.

All waste was crushed into small particles with the help of a crusher. The organic wastes from the UR were added directly to the garden waste at a ratio of 1:2.5 in each of the composters and mixed with the help of a tractor, resulting in a homogeneous mixture. Immediately after, the starter cultures were inoculated with direct applications of the reactivated inoculum on the mixture of residues. In the initial time, 5 liters of inoculum (both NCI and CI) plus 15 liters of water were used in each compost, except the compost with the control treatment.

Moisture content was controlled by the hand test consisting of “moistening and rubbing a little of the compost between the palms”, if the compost is ready, it will not get dirty, loosening easily, and kept between 50% and 60%, and irrigations are performed when necessary according to this standard throughout the composting process to maintain the ideal moisture content [31]. Irrigations were

performed on average every 3 days, with an average amount of 10 liters of water per compost each time [32].

The samples were collected in triplicate throughout the composting process. In the initial time were collected 3 samples of 1 to 10 cm, 3 samples of 45 cm and 3 samples of 90 cm, respectively. The sampling depth has changed throughout the process due to the reduction in the height of the piles, always maintaining the collection on the surface, interior and bottom of the pile. Surface, interior and bottom composting samples were homogeneously mixed for analysis and after 0, 60 and 120 days for the analysis of the physical and chemical dynamics. Samples were taken after 0, 5, 10, 20, 40, 60 and 120 days for the quantification of the microorganisms.

Step 3. Physicochemical Analyses

The physicochemical analyzes were performed during times 0; 60 and 120 days of composting. The moisture content was evaluated by drying at 105 °C until having the same weight with 3 readings followed. The lowering of the piles was measured using tape measure to follow the lodging of the material and the decomposition of the particles. The fertility of the composting were determined according to the Manual of Soil Analysis [33]. The following parameters were evaluated: C; N; C:N; H + Al (potential acidity); pH in H₂O; P-rem (remaining phosphorus); P available; K; SO₄; Na; Ca; Mg; S; B; Cu; Fe; Mn; Zn; organic matter (OM); organic carbon (OC); V (base saturation); m (aluminum saturation); SB (sum of bases); total CEC (cations exchange capacity) and effective CTC (Embrapa, 2011). The micronutrients were quantified using the Mehlich method [34].

Step 4. Microbiological Analyses

Microbial counting of cultivable microorganisms was carried out from inoculum and samples at intervals, 0; 5; 10; 20; 40; 60 and 120 days in triplicate. 25 g of each sample was added to 225 mL of sterile peptone water in a shaker at 120 revolutions per minute (rpm) for 30 min at room temperature [35]. The samples were mixed in a stomacher at normal speed for 60 s, and 10-fold dilutions were prepared.

Seven different types of culture media were used to study the microbial communities. Nutrient Agar (NA, Merck) was used as a general medium for the viable mesophilic bacteria population [36]. GYC (50 g glucose, 10 g yeast extract, 5 g CaCO₃ and 20 g agar) for acetic acid bacteria according [37]. MRS (De Man Rogosa Sharpe, Merck) agar containing 0.1% cysteine - HCl was used for Lactic acid bacteria growth under anaerobic conditions according [36]. MRS plates were incubated in acrylic anaerobic jars. After spreading, the plates were incubated at 28 for 48 h. The counting and isolation of actinobacteria were performed using Aaronson medium (2 g KNO₃, 0.8 g casein, 2 g NaCl, 2 g K₂HPO₄, 50 mg MgSO₄.7H₂O, 20 mg CaCO₃, 40 mg FeSO₄.7H₂O, 15 g agar), incubated at 45 °C for 72 to 120 h [38]. The counting and isolation of yeasts were performed using YEPG (10 g yeast extract, 10 g bacteriological peptone, 20 g glucose, 20 g agar with pH 3.5) and incubated at 28 °C for 48 h [39]. The filamentous fungi population

was counting using PDA (200 g raw potatoes, 20 g dextrose, 20 g agar, 1 L distilled water) and incubated at 25 °C for 7 days [40].

The morphological characteristics of the colonies (cell size, cell shape, edge, color, and brightness) were recorded and the square root of the number of colonies counted for each morphotype was purified by streaking on new agar plates [41].

The phenotypic characterization of the bacterial colonies was performed using Gram staining, catalase and oxidase activities and motility tests [42]. The pure cultures were stored in an ultra-freezer at -80 °C in the same broth culture media used for plating, containing 20% glycerol (w/w). Yeast colonies were characterized for morphology and biochemical assessments as described by [43]. Filamentous fungi were observed with an optical microscope for preliminary identification. This was done by morphotype analysis of the colony, especially color and appearance using the proposals of Pitt and Hocking, 1997.

Step 5. Experimental Design

The composting process consisted of three treatments: control (without inoculation), noncommercial inoculum (NCI) and commercial inoculum (CI), with 6 replicates, totaling 18 composters. The composters were distributed in a completely randomized design (CRD) in the parcel scheme subdivided in time. The data obtained during the composting process (chemical and microbiological parameters) were analyzed using the statistical software Sisvar and the principal components analysis using the STATISTICA 7.0 software.

Results

Step 1. Evolution of temperature

During the bio-oxidative phase, a maximum temperature of 65°C was reached for all treatments. High temperatures (thermophiles) (> 50°C) may be related to the gradual degradation of easily biodegradable material in the bio-oxidative phase, which produces a lot of energy, increased sharply the temperature [45].

Step 2. Physical and chemical dynamics

The physicochemical changes during the composting process are shown in Table 2 and Figure 3.

There was a tendency for humidity to decrease over time and between treatments. However, the variable moisture presented a fall, but not a constant, over time.

Table 2. Physical and chemical parameters during composting for Control, Efficient microorganisms and commercial inoculum treatments.

Treatment	Control			Efficient microorganisms			Commercial inoculum		
				Time (days)					
	0	60	120	0	60	120	0	60	120
C	21.6	20.2	19.1	21.8	19.1	13.6	24.5	15.4	14.2
N	0.9	0.9	0.9	1.2	1.2	1.2	1.2	1.2	1.2
C:N	24.1:1	16.8:1	15.9:1	24.2:1	15.9:1	11.3:1	27.2:1	12.8:1	11.8:1
Humidity	43.3	28.8	26.5	39.3	26.00	35.9	41.5	25.9	31.4
Pile Hight	100.00	58.6	53.00	100.00	58.4	51.4	100.00	63.00	50.6
Al	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
H+Al	3.2	0.8	0.8	3.5	0.7	0.9	5.2	0.8	0.8
pH H ₂ O	6.3	8.4	8.1	5.9	8.5	8.00	5.6	8.3	8.1
P rem	55.4	52.00	54.5	56.4	48.7	55.3	52.00	57.1	53.9
P available	379.2	394.1	423.2	245.4	257.6	545.9	292.00	318.2	577.4
K	15.3	16.7	15.5	11.7	16.5	12.3	10.6	16.4	13.4
SO ₄	456.2	74.9	119.2	360.7	63.1	127.00	302.4	113.8	93.5
Na	224.6	250.00	192.3	303.7	202.8	224.1	399.9	237.5	208.5
Ca	12.00	7.5	12.1	10.5	10.2	10.3	7.9	8.2	9.3
Mg	4.00	2.8	4.2	3.5	3.4	3.4	2.9	3.2	3.2
S	152.1	25.00	39.7	120.3	21.00	42.3	100.8	37.9	31.2
B	2.7	1.3	2.7	1.9	1.3	1.3	1.8	1.7	1.4
Cu	2.2	0.9	0.9	2.00	0.8	0.8	2.1	1.2	1
Fe	69.9	28.3	26.3	49.1	21.5	25.9	37.4	31.8	27.3
Mn	87.5	94.7	94.00	61.6	99.6	80.6	44.2	85.8	84.2
Zn	9.7	11.7	12.3	7.1	12.2	13.4	10.7	11.2	14.00
M.O	29.00	15.2	19.1	21.8	19.1	13.6	24.5	15.4	14.2
C.O	16.8	8.8	11.1	12.7	11.1	7.9	14.2	9.00	8.2
V	91.0	97.3	97.5	88.4	98.0	96.9	81.7	97.4	97.2
M	0.4	0.2	0.2	0.5	0.2	0.2	0.4	0.3	0.3
SB	32.3	28.1	32.7	27.1	31.1	26.9	23.1	28.8	26.8
Total CTC	35.5	28.9	33.5	30.6	31.7	27.7	28.3	29.6	27.6
Effective CTC	32.4	28.2	32.7	27.2	31.1	26.9	23.2	28.9	26.8

Reduction/lowering of pile hight measurement was measured in cm.

Al; H + Al; K, Na; Ca; Mg; SB; total CTC and effective CTC were measured in cmol/dm³.

The C:N ratio for NCI and CI compost samples decreased significantly with time and started stabilized after 60 days in NCI treatment (12.8) and 120 days in CI treatment (15.9). However, both samples showed C:N below 12 (11.8 and 11.3, respectively), and this rate indicated a direct mineralization of organic nitrogen [51]. Control showed C:N equal to 15.9 at the end of the composting process. It means that the process of composting without inoculum could not finished at 120 days. C: N ratio decreased as the degradation process proceeded (especially in NCI and CI) and C valorized mainly as carbon dioxide [52].

In general, the variables sodium, total acidity, base saturation index, copper, manganese and ion exchange capacity were the variables that most contributed to explain the variability of the data. The organic matter contents presented initial values of 29.0%, 21.8% and 24.5% and final values of 19.1%, 13.6% and 14.2%, showing decrease of 9.9%, 8.2% and 10.3% in the control, MS and IC treatments, respectively, throughout the process. In relation to the macronutrients, available phosphorus levels increased during the composting process, reaching 423.3 mg/dm³, 545.9 mg/dm³ and 577.4 mg/dm³ in the control, NCI and CI treatments, respectively. The initial values of K in the control, NCI and CI treatments were 15.3 cmol/dm³, 11.7 cmol/dm³ and 10.6 cmol/dm³, while the final values were slightly higher, with 15.5 cmol/dm³, 12.3 cmol/dm³ and 13.4 cmol/dm³. The Ca values remained constant, with an initial mean of 12.1 cmol/dm³ and a final average of 10.5 cmol/dm³. The Mg values increased with a change from 3.4 cmol/dm³ to 3.6 cmol/dm³. The opposite occurred with the values of S and Na, which decreased in both treatments throughout the process.

As higher the decomposition rate, higher was the mineralization rate of some nutrients at the end of composting and higher was the quality of the biofertilizer [58]. In terms of micronutrients, only Mn and Zn showed a significant increase during composting.

The principal component analysis (PCA) of the physical and chemical parameters obtained during composting. In this analysis, the principal components (PC) 1 and 2 explained 66.19% of the data variance (Figure 3).

With the physiochemical variables analysis, there was a high relation with PC1, that demonstrated the influence of treatment NCI and CI in results, only variables Cu, pH and degradation of organic material showed low relation with the PC1. In relation at PC2 the influence of CI treatment that showed high influence for Ca, Mg, lowering, Na, P-rem, B, S, C, pH and M.O available, already NCI showed influence for Cu and H + Al values (Figure 3).

Step 3. Microbial communities

The yeast population in the NCI inoculum was 5.5 log CFU g⁻¹, lower than the CI inoculum yeast count of 8.0 log CFU g⁻¹.

The aerobic mesophilic and thermophilic bacterial population remained stable during the composting process, with approximately 8.0 log CFU g⁻¹ of compost, even in the thermophilic phase (T5 and T10) in

both treatments (Figures 4a, b and c).

The population of actinobacteria remained constant only in the CI treatment (Figure 4c)), whereas in the control (Figure 4b)) and NCI (Figure a)) treatments there was a decrease in the population in the thermophilic phase (T5 and T10). The yeast population varied throughout composting time, showing similar behavior in all treatments (Figures a, b and c), with a lower population compared to bacteria and actinobacteria, remained stable in the first 20 days of composting, but after 40 days of composting showed no growth. The population of filamentous fungi remained stable, over time, in all treatments (Figures a, b and c), with approximately $5.0 \log \text{CFU g}^{-1}$ of compound.

Discussion

Step 1. Evolution of temperature

Temperature is one of the main parameters used to monitor the composting process and determine the decomposition rate of organic matter [7]. The thermal profile of the compost (Fig. 2) allowed to distinguish two phases: bio-oxidative (40 days) and maturation phase (80 days) independent on the treatment, totalling 120 days of composting, which can be considered a viable process, since other authors such as Jurado et al. (2014) [44], totaled the process at 189 days of composting. Regardless of time, the composting process is advantageous because it happens the recycling of materials that could be polluting or cause public health problems.

The temperature profile showed rapid increase, reaching 60°C during the first day. These results indicated that there was a satisfactory nutrient balance [28, 46]. The thermophilic phase is important to annihilate the potential pathogen, weed and sanitizing the compost [35]. The composting process has to maintain at a thermophilic temperature of a minimum of three consecutive days to inactivated the pathogen growth [47].

In the present study, the 3 treatments followed this trend, but NCI and control maintained an average 5°C higher than CI. The end of the bio-oxidative phase exhibited fluctuations in temperature and was followed by a cooling phase at which point the temperature was approximately 40°C (Fig. 2), which is characteristic of a stable mesophilic phase [5].

The temperature profiles for the composting process with NCI, CI and control treatment showed similar trend (Fig. 2). Temperature increased dramatically within the first few days of the composting process and decreased gradually after reaching the peak around 15–18 days. Increased temperature is caused by heat generation from the microbial metabolism by the respiration and decomposition of the substrate. Therefore, this profile might be significantly affected by microbial inoculum if the input material does not have sufficient microbial population for the degradation process [28]. The control and NCI treatments presented approximately 5 to 7°C higher than the CI throughout the composting process, resulting in the stabilization of this compost several days in advance.

Step 2. Physical and chemical dynamics

Aeration is one of the key parameters in controlling the activities of the waste being composted, as it influences the temperature, moisture and O₂ supply to the microorganisms. In the composting process, the predominant microorganisms are aerobic, therefore, they need oxygen to survive and maintain their metabolism [48]. The oxygen present in composting also removes excess moisture from the composting mass, avoiding the need for higher temperatures [49].

The process of assimilation of nutrients by microorganisms occurs through their cell walls, so that the metabolic activities organic matter degradation can occur, it is necessary that the humidity of the medium is adequate [49]. Despite periodic moistening, humidity did not always remain around 50% to 60% which was ideal, but around 40%. According to [46], mixtures of residues that have low moisture (under 50%) content inhibit microbial activity, because in any other biological process, water is essential for metabolism. However, by means of periodic moistenings, a value was guaranteed that did not restrict biological activities.

The reduction in height of the compost pile can be indicative of process evolution due to the decomposition of the parent material into smaller particles, which implies the reduction of the porosity of the pile.

One goal of the present study, which used garden waste and restaurant waste, was to assess the composting substrates, including the adjustment of the C/N ratio and any increases in the availability of nutrients. Karadag et al. (2013) [50] observed that carbon and nitrogen used by microorganisms for energy and growth resulted in changes in the C/N ratio during the composting process. During the composting process, organic matter degradation resulted in carbon reduction, which decreased at the end of composting (Table 2).

The variation of total acidity and pH value is a result of organic acids production by microbial metabolism [53]. The increase in pH value and the decrease in the exchangeable acidity (H+Al) (Table 2) are characteristics of a mature compost and resulted in increased degradation of organic acids and amino acids, which provides additional nutrients [54, 55]. The pH values in all treatments turned from acidic to a range of neutral and weakly alkaline indicating the stability of organic matter. The pH value at the first weeks was acidic (5.6 – 6.3) (Table 2). It gradually turned basic (8.0 – 8.1) due to the releases of ammonia (Table 2) [24] and conversion of organic acid into CO₂ by microbial activity [56].

The increase in P availability during composting may be related to organic matter degradation, increase in pH and decrease in Fe content in all treatments (Table 2), and also the activity of phosphatase, which is produced by phosphate-solubilizing microorganisms [57].

The nutrients are not volatile, therefore, the increase in the total content of P and K, for example, was mainly due to the loss of compost mass due to the biodegradation of organic content, that is, the content of these nutrients increases the metabolic activity of the microorganisms during composting and thus

increases the organic waste decomposition process [59]. This showed that the increase of the contents of these elements in both treatments, indicated a satisfactory rate of decomposition, in spite of the decrease in the contents of some nutrients, which were not significant.

Regarding the physical and chemical characteristics of the composting process, it was observed that the inoculation of the non-commercial and the commercial inoculum did not significantly differentiate from the natural composting process (Table 2).

These results of PCA showed the clear influence of the inoculation treatments in relation the control treatment, with better efficiency of CI in relation at the NCI treatment (Figure 3).

Fan et al. (2018) [28] noted that factors such as the humification process, fat reduction and N content are altered when non-commercial inoculum are inoculated into the composting process. Studies on the suitability of different inoculants are still inconclusive, likely due to the complexity of the composting process and the nature of organic wastes [2]. Studies by [60] have demonstrated that inoculation using a mature compost may be more indicative than the inoculation of starter cultures in the composting process, as there was no significant effect on the composting time and quality of the final compost. Likewise, [61] reported that inoculation with lignocellulosic microbiota was not effective in kitchen waste composting when compared to control treatments.

Step 3. Microbial communities

Compost maturity is reached when microbiological decomposition is complete and is accompanied by the mineralization of the components, making them available to the plants, and improving the physical, chemical and biological properties of the soil [62]. According to [46], mixtures of waste with low moisture content inhibit microbial activity. However, periodic irrigation ensured a moisture content that did not limit the microbial population in different treatments (Figure 4).

During all process of composting, in both of treatments, the population of prokaryotes (bacteria and actinobacteria) was higher than that of eukaryotes (fungi and yeasts), as also observed by [35]. Even the beginning of the bio-oxidative phase presenting high temperatures ($>50^{\circ}\text{C}$), thermotolerant mesophilic microorganisms are able to withstand this treatment [63]. Even when there is no change in the total plate count of microorganisms, there may be a reduction in diversity indices, which may favor certain microbial groups [64].

The inoculation of the NCI and CI did not influence the composting process. Microbial communities were similar throughout the process in both treatments. In composts without the addition of starter cultures, several changes naturally occur in the physical and chemical structure, because the microorganisms present are capable of biological activity to increase the temperature ($55-70^{\circ}\text{C}$), which provides the dominance of thermophilic microorganisms with high degradability of organic matter [45]. Thus, the endogenous populations of microorganisms adapt to environmental variations provided by the

composting process and plays an important role in the degradation of organic matter, mineralization of nutrients, control of pathogens, and stabilization of the compost [45, 64].

Conclusions

The new type of bioreactor shown to be efficient and helped accelerate decomposition of composted material. The analysis of organic matter transformation during the composting of organic wastes showed complex physical, chemical and microbiological interactions. The treatments with the NCI and CI inoculum presented advantages in terms of the quality of the final product in comparison to the control treatment. During the composting process, in both treatments, there was a greater mineralization of P-available and micronutrients as Mn and Zn, which indicates that the compound can be used as a biofertilizer, however requiring additional tests and studies.

Although not the objective of this work, microbiome studies are needed as a tool to better understand the role of microorganisms in nutrient cycling in the compost.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Authors' contributions

SSG contributed to setting up and conducting the experiment, laboratory analysis, data analysis and article writing. LLRA and CAC contributed to the assembly and conduct of the experiment and laboratory analysis. GMR, RFS and JDRS contributed to data analysis and article writing.

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Figures

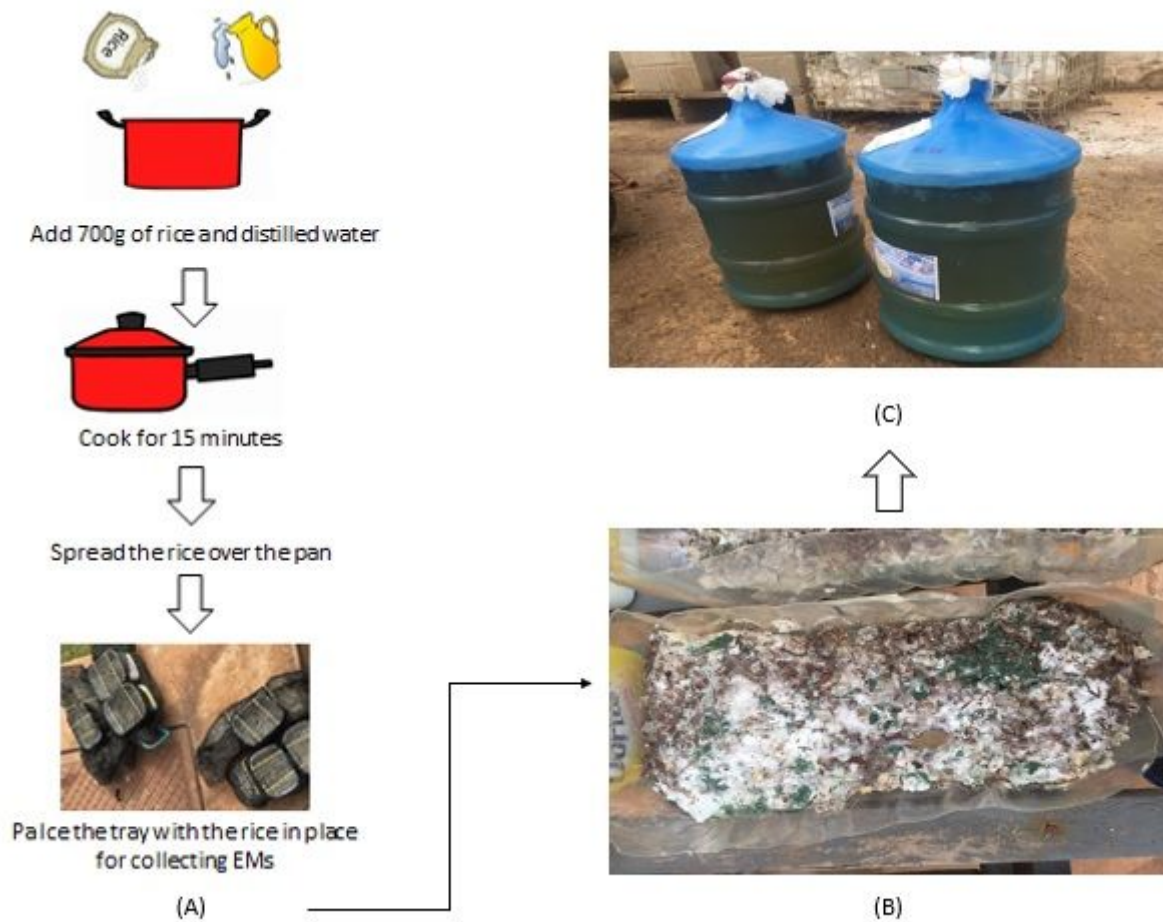


Figure 1

Process of obtaining and activating NCIs. A - Procedures for capturing MS's; B - Aspect of the rice containing the MS before the activation; C - Activation of NCI in sugarcane juice [20] (with adaptations).

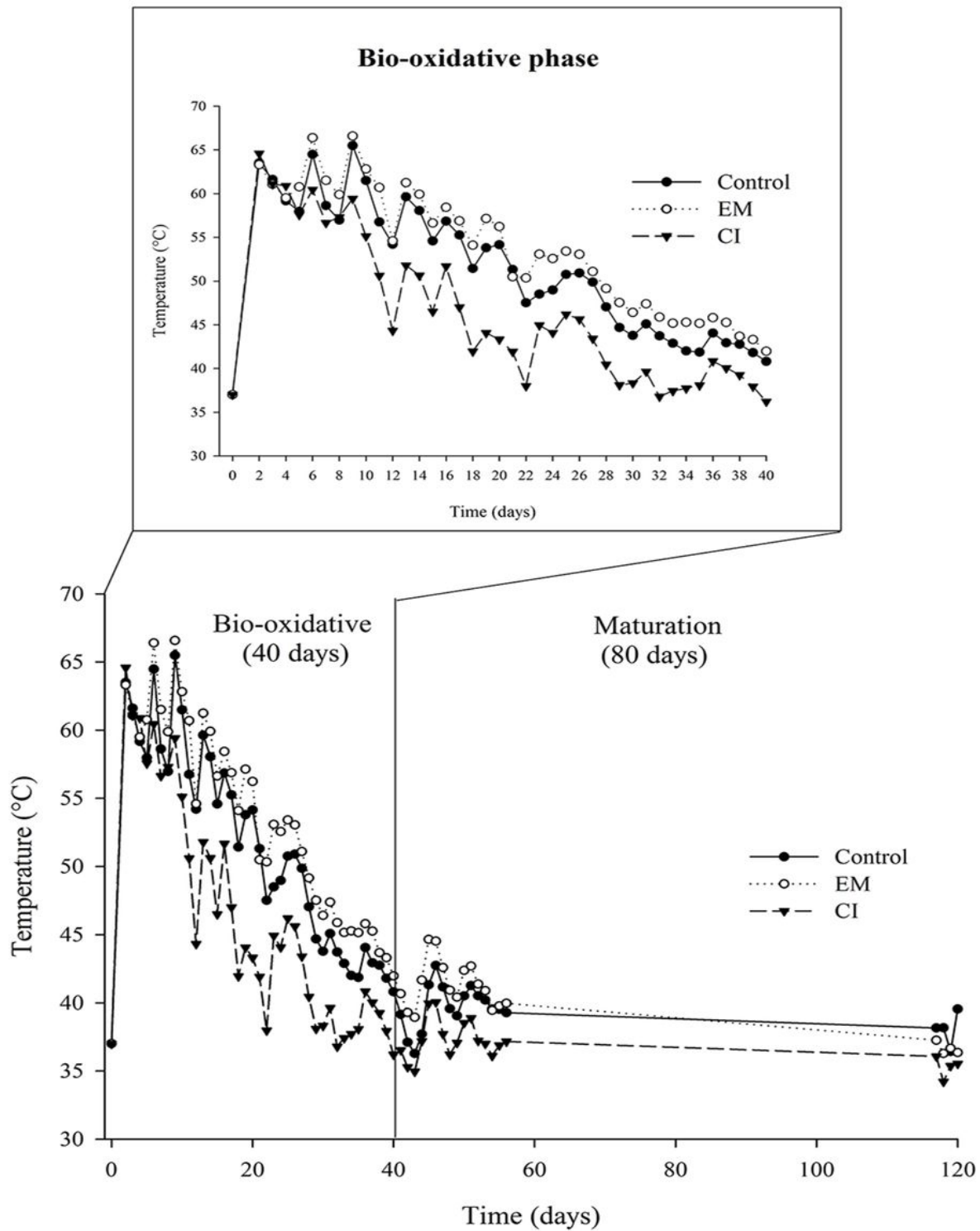


Figure 2

Thermal profile (C°) of the three treatments Control; Efficient microorganisms (NCI) and commercial inoculum (CI) during the composting process.

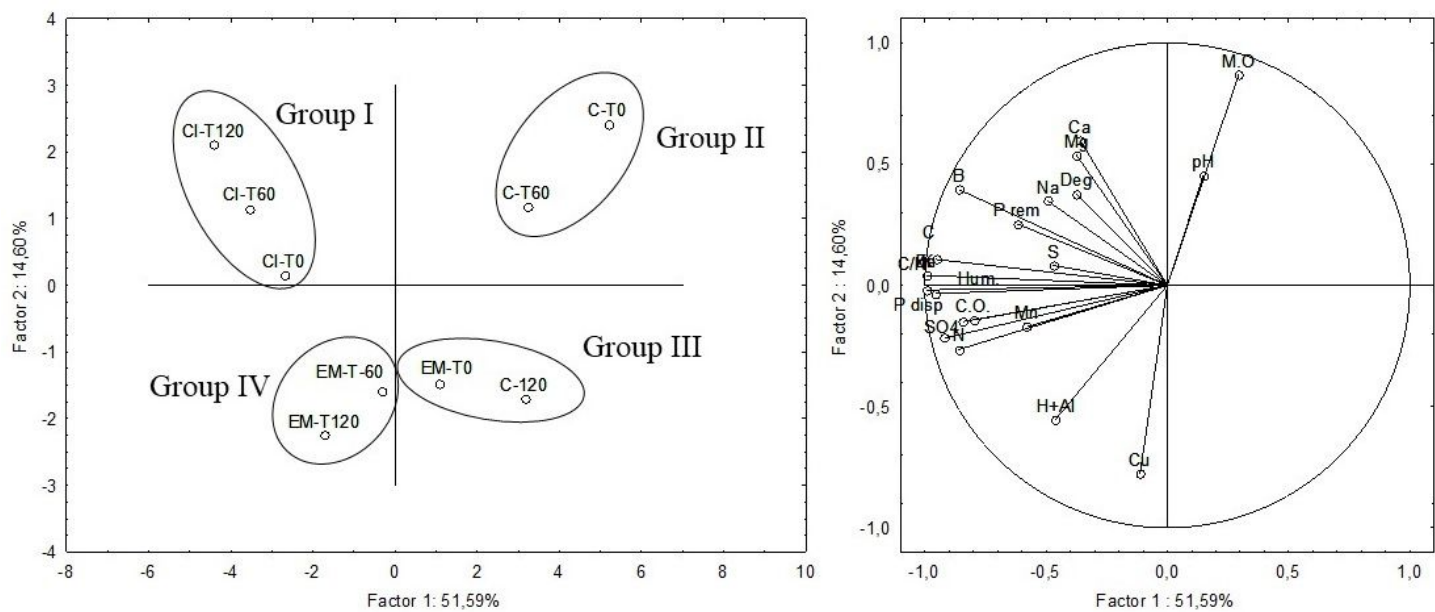


Figure 3

Analysis of major components of physical and chemical attributes during composting.

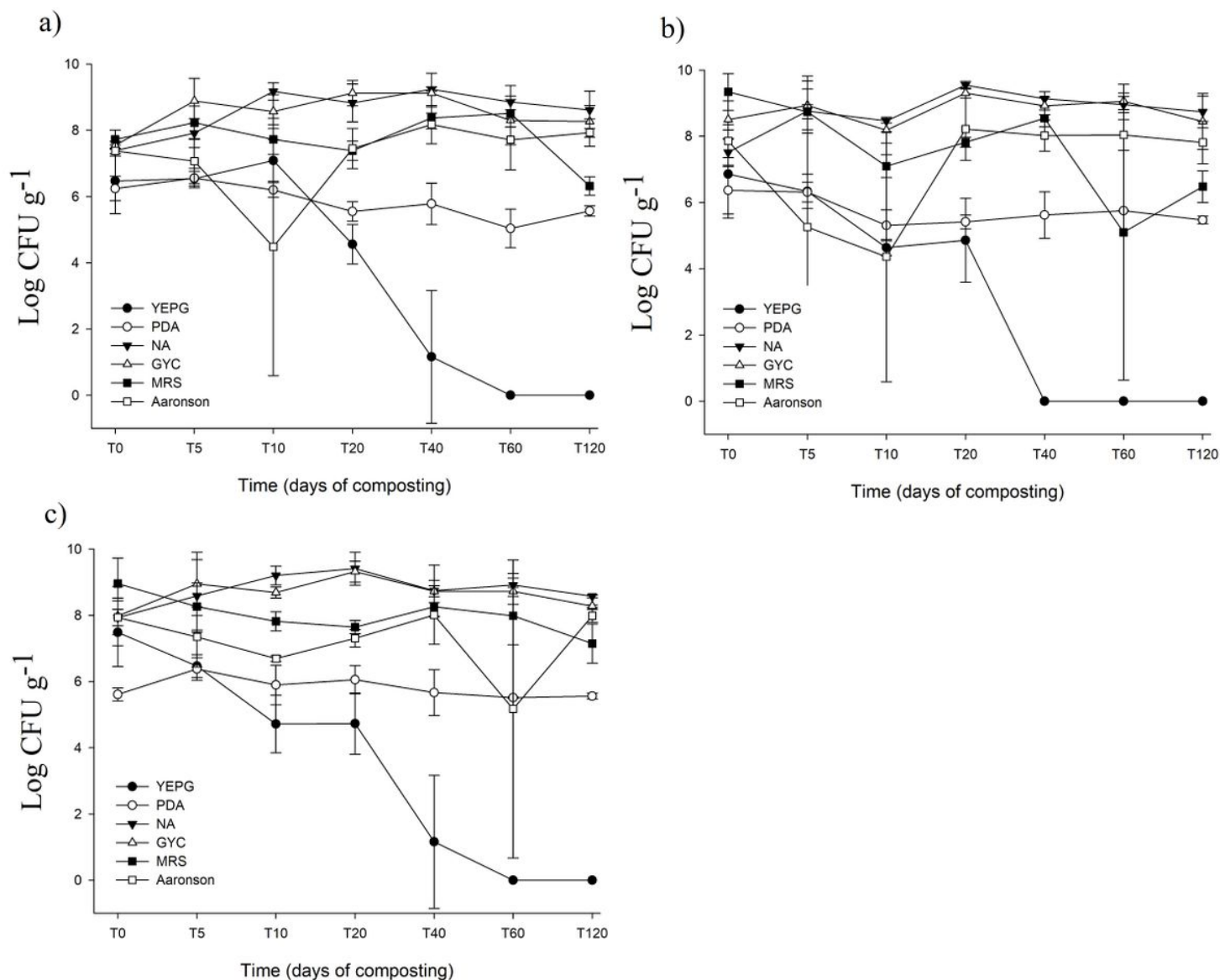


Figure 4

Variation in the total count of microorganisms (log UFC g⁻¹ of compost) during composting. a) Treatments with efficient microorganisms; b) Control treatment; c) Treatment with commercial inoculum. Means: YEPG - yeast; PDA - Filamentous fungi; NA - Total mesophilic bacteria; MRS - Lactic bacteria; GYC - Bacteria of acetic acid and Aaronson – Actinobacteria.

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